Guest Editorial
Recent Advances in Capacity Approaching Codes

Erdal Arıkan, *Fellow, IEEE*, Daniel J. Costello, Jr., *Life Fellow, IEEE*, Joerg Kliewer, *Senior Member, IEEE*, Michael Lentmaier, *Senior Member, IEEE*, Paul Siegel, *Fellow, IEEE*, Ruediger Urbanke, *Senior Member, IEEE*, and Michael Pursley, *Life Fellow, IEEE*

SINCE the "turbo revolution" of 1993 and the "rediscovery" of low-density parity-check (LDPC) codes shortly thereafter, the world of channel coding has undergone a major transformation. The "conventional wisdom" of the 1960s, 1970s, and 1980s was that, although capacity was theoretically achievable, practical constraints typically limited the performance of implementable code designs to fall several decibels short of capacity. This understanding was shattered with the invention of turbo codes, which achieved performance roughly 0.5 dB from capacity with moderately complex iterative BCJR decoding, and within just a few years, capacity approaching schemes using LDPC codes along with linear (in block length) complexity message passing decoding were becoming commonplace.

Past issues of JSAC have been in the forefront of keeping the research community current with the latest trends in capacity approaching codes. In February 1998, JSAC published *Concatenated Coding Techniques and Iterative Decoding: Sailing Towards Channel Capacity*, edited by S. Benedetto, D. Divsalar, and J. Hagenauer. The issue contained 16 papers, all of which dealt with some aspect of turbo codes. Then in May and September of 2001, JSAC published *The Turbo Principle: From Theory to Practice I* and *The Turbo Principle: From Theory to Practice II*, edited by P. Siegel, D. Divsalar, E. Eleftheriou, J. Hagenauer, and D. Rowitch. Part I contained 17 papers, 14 devoted to various types of turbo codes, and 3 on LDPC codes. Part II contained 15 additional papers related to applications of the turbo principle in other areas of communication theory. Then in August 2009, JSAC published *Capacity Approaching Codes*, edited by D. Costello, S. Lin, T. Richardson, B. Ryan, R. Urbanke, and R. Wesel. A total of 18 papers were published, 11 on LDPC codes, 4 on turbo codes, and 3 on other coding-related topics, indicating a clear shift in the interests of the research community toward LDPC codes.

The current JSAC special issue reflects a further shift of interest in coding theory research, this time toward polar codes, a new class of *capacity achieving* codes introduced in 2008. Of the 17 papers appearing in this issue, 9 are devoted to various aspects of polar codes, with 6 papers devoted to LDPC codes, including 3 on spatially coupled (convolutional) LDPC codes, and 2 on other coding topics. Below we give a brief summary of each paper, starting with the papers on polar codes.

I. Polar Codes

The issue begins with an historical overview paper by E. Arikan on the origins of polar coding. It starts by reviewing the role that the channel cut-off rate R_0, sequential decoding of convolutional codes, and the successive-cancellation framework played in the development of polar codes and concludes by explaining the polar coding concept from this perspective. Of particular interest is the notion that polar codes were originally intended to be the inner code in a concatenation scheme with a convolutional outer code paired with sequential decoding. However, the polar coding concept by itself turned out to be so powerful that no outer code was needed.

The eight other papers on polar codes investigate various aspects of polar code design, decoding techniques, and extensions. The paper by Renes *et al.* deals with the *alignment* of polarized codes and how this relates to the notion of *universality*. Two conditions are derived, one for alignment and one for nonalignment, and the set of channels for which alignment occurs, implying universality, is expanded compared to what was previously known.

The paper by Presman *et al.* introduces a novel construction for polar codes, called a *mixed-kernel* construction, based on code decomposition. Channel polarization is proven for the new construction, and mixed-kernal polar codes are shown to have performance and decoding complexity advantages in the finite block length regime.

The paper by Trifonov and Miloslavskaya introduces the concept of *dynamic frozen bits* and shows how these can be used to describe certain *subcodes* of an arbitrary linear block code as polar codes. This allows larger minimum distances to be achieved, thereby improving the finite block length scaling behavior.

E. Arıkan is with the Department of Electrical and Electronic Engineering, Bilkent University, Ankara 6800, Turkey (e-mail: arikan@ee.bilkent.edu.tr).

D. J. Costello, Jr. is with the Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556 USA (e-mail: costello.2@nd.edu).

J. Kliewer is with the Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102 USA (e-mail: jkliewer@njit.edu).

M. Lentmaier is with the Department of Electronics and Information Technology, Lund University, Lund SE-221 00, Sweden (e-mail: michael.lentmaier@eit.lth.se).

P. Siegel is with the Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, CA 92093 USA (e-mail: psiegel@ucsd.edu).

R. Urbanke is with the Communication Theory Laboratory, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne CH-1015, Switzerland (e-mail: ruediger.urbanke@epfl.ch).

M. Pursley is with the Department of Electrical and Computer Engineering, Clemson University, Clemson, SC 29634 USA (e-mail: pursley@ces.clemson.edu).

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The paper by Wang *et al.* considers the serial concatenation of an inner polar code with outer BCH and convolutional codes, a combination suggested in the overview paper by Arikan. The major result is to demonstrate that this combination provides an efficient tradeoff between error-correction performance and decoding complexity.

The paper by Wei and Ulukus presents a polar coding scheme that achieves the information-theoretic capacity of the *general wiretap channel* and applies the results to a number of *multiuser channels* to achieve their best-known inner bounds. As such, the polar coding approach serves as a bridge between recent results in information-theoretic security and emerging applications in wireless communications.

The paper by Zhang *et al.* proposes a modified low complexity *successive cancellation list* (SCL) decoder for polar codes that relies on the idea that path splitting may be unnecessary when the reliability of an unfrozen bit is sufficiently high. The modified SCL decoder is shown to achieve a significant reduction in decoding time with only a slight penalty in error-correction performance compared to a conventional SCL decoder.

The paper by Fan *et al.* pursues a related concept called *selective expansion* along with a *double thresholding* list-sorting algorithm to reduce the latency of SCL decoding implementations of polar codes. A VLSI implementation using CMOS technology is then used to demonstrate that the resulting penalty in error-correction performance is negligible.

Finally, the paper by Sarkis *et al.* also deals with SCL decoder implementations for polar codes. In particular, software implementations of fast SCL decoders, which make use of a method of *unrolling* the decoding tree to improve speed, are demonstrated and compared. An application to software-defined radio is also included.

II. Spatially Coupled Codes

The paper by Liu *et al.* introduces a new algebraic construction method for *spatially coupled* (convolutional) LDPC (SC-LDPC) codes, called *replicate-and-mask* (R&M). The R&M method, which has been previously employed to construct good *quasi-cyclic* LDPC block codes, is extended to construct quasi-cyclic SC-LDPC codes with guaranteed girth, and the new codes are compared to conventional quasi-cyclic SC-LDPC codes obtained using the unwrapping method.

The paper by Stinner and Olmos analyzes the *finite-length scaling* behavior on the binary erasure channel (BEC) of structured SC-LDPC codes constructed using *protographs*, thus extending previous work by the second author for random code ensembles. The results indicate that the additional structure imposed by protograph-based ensembles improves the finite-length scaling performance.

The paper by Huang and Ma is devoted to a performance analysis of *Block Markov Superposition Transmission* (BMST) codes, a type of serially concatenated code with easy encoding that uses short block codes as component codes. The encoding method is shown to be equivalent to *spatial coupling* of the generator matrix, and performance comparisons to SC-LDPC codes and ARJA-type LDPC block codes indicate excellent waterfall region behavior.

III. LDPC Codes

The paper by Ganesan *et al.* investigates the important practical problem of determining the total power, including both *transmit power* and *decoding power*, needed to guarantee a certain hard-decision iterative decoding error probability for a class of LDPC codes operating on the AWGN channel. Two models of decoding power are considered, where all the power is consumed either by the processing nodes or by the wires, and analytical bounds are obtained in each case.

The paper by Steiner *et al.* considers the joint optimization of protograph-based LDPC code ensembles and bit mapping for shaped bandwidth-efficient bit interleaved coded modulation (BICM) on the AWGN channel. *Constellation shaping* and *bit-level reliabilities* are taken into account in the optimization, and ensembles are found that outperform the best currently known designs for bandwidth-efficient coded modulation with shaping.

The paper by Mitchell *et al.* investigates the iterative decoding thresholds of high-rate LDPC code ensembles derived from a lower rate mother code ensemble by *random puncturing*. In particular, it is shown that the BEC and AWGN thresholds of randomly punctured LDPC code ensembles can be accurately predicted using a single constant, which depends only on their design rate and the BEC threshold of the mother code ensemble.

IV. Coding Theory

The paper by Lazaro *et al.* analyzes the minimum distance properties of *fixed-rate raptor codes* with linear random codes as outer codes. The *average weight enumerator* is formulated and necessary and sufficient conditions for fixed-rate raptor code ensembles to achieve *linear minimum distance growth* are derived, where the weight enumerator and the distance growth rate are expressed as functions of the rate of the outer code and the degree distribution of the inner LT code.

V. Coding Applications

The paper by Zeineddine and Mansour presents a two-step coding scheme for application to time-varying channels in wireless broadcast communications. In the proposed scheme, frames are encoded individually and then a second layer of *interframe* coding is applied across frames. This structure leads to an *iterative rate-matching decoding* process, which is shown to result in a better complexity versus data-rate tradeoff than previously existing approaches.

VI. Summary

This special issue captures a snapshot of the continuing evolution of research interests in the fascinating area of capacity approaching codes. Once it was understood by researchers that it was possible to implement practical coding schemes with near-capacity performance, the digital communications and data storage industries, along with the associated standards committees, quickly took note of the new methods. Turbo codes were adopted for several coding standards in the late 1990s, shortly followed by LDPC coding standards in the 2000s. Now, reflecting the shift in research interests noted in this special issue, both polar codes and spatially coupled LDPC codes are being actively considered for future coding standards. This activity underscores the remarkable staying power of channel coding theory as a research topic of great theoretical and practical interest over a span of time that now exceeds 60 years.

Acknowledgment

We would like to thank all the authors who submitted their research papers to the special issue. We particularly appreciate their efforts to submit their materials in a timely manner. The overall quality of the submissions was very high, and we regret that, due to space and time constraints, we could not have accepted more papers. Special thanks are also due to the reviewers, who were very responsive to our repeated reminders about staying on schedule. Their critical comments and suggestions to the authors contributed greatly to the final product. We are also thankful to M. Medard, JSAC Editor-in-Chief, Executive Editor L. Greenidge, and Editorial Assistant L. Briede at IEEE Publishing Operations for the co-operation and encouragement they have provided to this project. Finally, thanks are due to the JSAC Editorial Board Representative M. Pursley for suggesting to us that "it might be time for another special issue on coding" and for presiding over the guest editor submissions.

Erdal Arıkan (S'84–M'79–SM'94–F'11) was born in Ankara, Turkey, in 1958. He received the B.S. degree from the California Institute of Technology, Pasadena, CA, USA, in 1981, and the S.M. and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, MA, USA, in 1982 and 1985, respectively, all in electrical engineering. Since 1987, he has been with the Electrical-Electronics Engineering Department, Bilkent University, Ankara, Turkey, where he works as a Professor. He was the recipient of the 2010 IEEE Information Theory Society Paper Award and the 2013 IEEE W.R.G. Baker Award, both for his work on polar coding.

Daniel J. Costello Jr. (S'62–M'69–SM'78–F'85–LF'08) received the Ph.D. degree in electrical engineering from the University of Notre Dame, Notre Dame, IN, USA, in 1969. Since 1985, he has been a Professor of Electrical Engineering, University of Notre Dame, and from 1989 to 1998, served as the Chair of the Department. In 2000, he was named the Leonard Bettex Professor of Electrical Engineering. He has numerous technical publications in his field, and in 1983, he coauthored a textbook entitled *Error Control Coding: Fundamentals and Applications* (2nd edition, 2004). His research interests include digital communications, with emphasis on error control coding and coded modulation. He was elected an IEEE Fellow in 1985. He was the recipient of the Third-Millennium Medal from the IEEE Information Theory Society in 2000. He was also the recipient of the 2013 IEEE Information Theory Society Aaron D. Wyner Distinguished Service Award and the 2015 IEEE Leon J. Kirchmayer Graduate Teaching Award. He was the corecipient of the 2009 IEEE Donald G. Fink Prize Paper Award and the 2012 ComSoc & Information Theory Society Joint Paper Award.

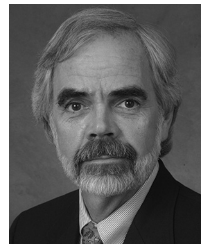
Joerg Kliewer (S'97–M'99–SM'04) received the Dipl.-Ing. (M.Sc.) degree from Hamburg University of Technology, Hamburg, Germany, and the Dr.-Ing. degree (Ph.D.) from the University of Kiel, Kiel, Germany, both in electrical engineering, in 1993 and 1999, respectively. From 1993 to 1998, he was a Research Assistant with the University of Kiel, and from 1999 to 2003, he was a Senior Researcher and Lecturer with the same institution. In 2004, he visited the University of Southampton, Southampton, U.K., for one year, and from 2005 to 2007, he was with the University of Notre Dame, Notre Dame, IN, USA, as a Visiting Assistant Professor. From 2007 to 2013, he was with New Mexico State University, Las Cruces, NM, USA, most recently as an Associate Professor. He is now with the New Jersey Institute of Technology, Newark, NJ, USA, as an Associate Professor. His research interests include span coding and information theory, graphical models, and statistical algorithms, which includes applications to networked communication and security, data storage, and biology. He was an Associate Editor of the IEEE Transactions on Communications from 2008 to 2014, and since 2015 serves as an Area Editor for the same journal. He has also been a member of the Editorial Board of the IEEE Information Theory Society Newsletter since 2012. He was the recipient of the Leverhulme Trust Award and the German Research Foundation Fellowship Award in 2003 and 2004, respectively.

Michael Lentmaier (S'98–M'03–SM'11) received the Dipl.-Ing. degree in electrical engineering from the University of Ulm, Ulm, Germany, and the Ph.D. degree in telecommunication theory from Lund University, Lund, Sweden, in 1998 and 2003, respectively. He worked as a Postdoctoral Research Associate with the University of Notre Dame, Notre Dame, IN, USA, and with the University of Ulm. From 2005 to 2007, he was with the Institute of Communications and Navigation of the German Aerospace Center (DLR), Oberpfaffenhofen, Germany, where he worked on signal processing techniques in satellite navigation receivers. From 2008 to 2012, he was a Senior Researcher and Lecturer with the Vodafone Chair Mobile Communications Systems, TU Dresden, Germany, where he was heading the Algorithms and Coding Research Group. Since January 2013, he has been an Associate Professor with the Department of Electrical and Information Technology, Lund University. His research interests include design and analysis of coding systems, graph-based iterative algorithms, and Bayesian methods applied to decoding, detection, and estimation in communication systems. He served as an Editor for the IEEE Communications Letters from 2010 to 2013 and the IEEE Transactions on Communications since 2014. He was the recipient of the Communications Society and Information Theory Society Joint Paper Award (2012) for his paper "Iterative Decoding Threshold Analysis for LDPC Convolutional Codes."

Paul Siegel (M'82–SM'90–F'97) received the S.B. and Ph.D. degrees in mathematics from Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, in 1975 and 1979, respectively. He held a Chaim Weizmann Postdoctoral Fellowship with the Courant Institute, New York University, New York, NY, USA. He was with the IBM Research Division, San Jose, CA, USA, from 1980 to 1995. He joined the Faculty with the University of California, San Diego, CA, USA, in July 1995, where he is currently a Professor of Electrical and Computer Engineering in the Jacobs School of Engineering. He is affiliated with the Center for Magnetic Recording Research where he holds an Endowed Chair and served as Director from 2000 to 2011. His research interests include information theory and communications, particularly coding and modulation techniques, with applications to digital data storage and transmission. He was a Member of the Board of Governors of the IEEE Information Theory Society from 1991 to 1996 and again from 2009 to 2014. He served as Co-Guest Editor of the May 1991 Special Issue on "Coding for Storage Devices" of the IEEE Transactions on Information Theory. He served the same Transactions as Associate Editor for Coding Techniques from 1992 to 1995, and as Editor-in-Chief from July 2001 to July 2004. He was also Co-Guest Editor of the May/September 2001 two-part issue on "The Turbo Principle: From Theory to Practice" of the IEEE Journal on

SELECTED AREAS IN COMMUNICATIONS. He is a member of the National Academy of Engineering. He was the 2015 Padovani Lecturer of the IEEE Information Theory Society. He was the recipient of the 2007 Best Paper Award in Signal Processing and Coding for Data Storage from the Data Storage Technical Committee of the IEEE Communications Society. He was the corecipient of the 1992 IEEE Information Theory Society Paper Award and the 1993 IEEE Communications Society Leonard G. Abraham Prize Paper Award.

Ruediger Urbanke (AM'11–M'12–SM'13) received the Dipl.Ing. degree from the Vienna University of Technology, Vienna, Austria, and the M.Sc. and Ph.D. degrees in electrical engineering from Washington University, St. Louis, MO, USA, in 1990, 1992, and 1995, respectively. From 1995 to 1999, he held a position with the Mathematics of Communications Department, Bell Labs, Murray Hill, NJ, USA. Since November 1999, he has been a Faculty Member with the School of Computer and Communication Sciences (I&C), EPFL, Lausanne, Switzerland. He has coauthored the book *Modern Coding Theory* (Cambridge University Press). His research interests include analysis and design of iterative coding schemes, and more broadly on the analysis of graphical models and the application of methods from statistical physics to problems in communications. From 2000 to 2004, he was an Associate Editor of the IEEE TRANSACTIONS ON INFORMATION THEORY and he is currently a Distinguished Lecturer of the Information Theory Society. He was the recipient of the Fulbright Scholarship, and a corecipient of the 2002 and 2013 IEEE Information Theory Society Paper Award, the 2011 Koji Kobayashi Award as well as the 2014 IEEE Hamming Medal.



Michael Pursley (S'68–M'68–SM'77–F'82–LF'11) was with the Department of Electrical and Computer Engineering and the Coordinated Science Laboratory, University of Illinois, Urbana-Champaign, IL, USA, for nearly 20 years before moving to Clemson University, Clemson, SC, USA, where he has been the Holcombe Endowed Chair in Electrical and Computer Engineering since 1992. He has served on the Board of Governors of the IEEE Information Theory Society, and he was the Elected President of that society in 1983. He was a member of the Editorial Board of the PROCEEDINGS OF THE IEEE during 1984–1991, and he is currently a Senior Editor of the IEEE JOURNAL OF SELECTED AREAS IN COMMUNICATIONS. He has served as the Technical Program Chairman and as a Co-Chairman for the IEEE International Symposium on Information Theory. He was named an Outstanding Electrical Engineer by the Purdue University School of Electrical and Computer Engineering in 2008. He was the recipient of the IEEE Communications Society Edwin Howard Armstrong Achievement Award in 2003 and the University of Southern California Viterbi School of Engineering Distinguished Alumni Award in 2005.